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Research Article

Discrimination between falls and blows from the localization and the number of fractures on computed tomography scans of the skull and the trunk

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Abstract

The distinction between falls and blows is a common and difficult task in forensic sciences. One of the most often used criteria to address this issue is the hat brim line (HBL) rule, which states that fall-related injuries do not lie above the HBL. Some studies, however, have found that the use of HBL rule is not so relevant. This study assesses the aetiologies, the number of fractures, and their location on the skull and the trunk in a sample of 400 individuals aged 20–49 years, which were CT scanned after traumas. This may facilitate the interpretation of such injuries in skeletonized or heavily decomposed bodies in which soft tissues are no longer available. Our aim is to improve the distinction rate between falls and blows by combining several criteria and assessing their predictability. Skeletal lesions were analysed using retrospective CT scans. Cases selected comprise 235 falls and 165 blows. We registered the presence and the number of fractures in 14 skeletal anatomical regions related to the two different aetiologies. We showed that the HBL rule should be used with caution, but there is nevertheless a possibility of discussing the aetiology of blunt fractures. Possibly, parameters like the anatomical location and the number of fractures by region can be used to distinguish falls and blows.

Keywords: forensic sciences; blunt force trauma; falls; blows; skeletal fractures; CT scan

Introduction

One of the key roles of the forensic anthropologist, in collaboration with the pathologist, is to provide analysis and interpretation of skeletal trauma. They can afford an expert opinion on the death circumstances by inferring the mechanism of trauma from the skeletal fractures [1, 2].

Blunt force trauma (BFT) can be caused by a blunt object or a surface, as in transportation fatalities, falls, or interpersonal violence [3–5]. The highly variable nature of this type of trauma makes it complicated and difficult to interpret on the basis of the skeletal characteristics only.

Moreover, BFT is one of the most common injuries encountered by the forensic expert [1]. Therefore, the expert has to try to determine if the injury is induced by blows or related to a fall [1, 6]. To achieve this, the hat brim line (HBL) rule has often been used [6–9]. Nevertheless, this distinction remains a challenge, mainly because of a lack of objectivity and standardized methods.

This study aims to investigate whether circumstances of traumatic events have an influence on the fractures they create and on their distribution on the skeleton (skull and trunk).

If so, the second objective will be to check whether we can propose a method helping to define the aetiology of observed fractures.

Materials and methods

Study sample

A retrospective review of post-traumatic living individuals who were computed tomography (CT) scanned between 2008 and 2019 identified 400 cases of falls and blows, with at least one fracture. CT scans of these polytraumatized individuals were performed at the Assistance Publique-Hôpitaux de Marseille (AP-HM, France), the Centro Hospitalar e Universitário de Coimbra, and the Centre Hospitalier Regional et Universitaire de Nancy. These scans were anonymized and collected

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from the Picture Archiving and Communication System. The clinical management of the patients rarely required a full-body scan. According to medical indications of CT scans, the skeleton had to be considered in two parts: on the one hand, the cranium and the mandible; and, on the other hand, from the first cervical to the pelvis, without the appendicular skeleton (i.e. the spine, the thorax, the shoulder and pelvic girdles, and the upper end of the femur).

The scanner slices were 0.6 and 1.25 mm thick according to the acquisition protocol. We selected adults aged between 20 and 49 years old to have a certain homogeneity in the physicochemical properties of the bone.

Medical information for each of these cases, as well as case details relevant to the circumstances causing the BFT, was reviewed. Since this is a retrospective study, based on clinical management of a patient, not all information about the circumstances of fractures are systematically indicated. So, we have no data on the number of perpetrators or blows in blow injuries. Furthermore, whenever possible, the characteristics of the individuals were recorded. Details included the following data:

Circumstances of BFT:

- Date of the traumatic event
- Type of BFT (falls or blows)
- Date of CT scan
- Height of the fall (when the medical report gives this information)
- Blunt force object used (when the medical report gives this information)

Characteristics of the individuals:

- Age
- Sex

Following the standards of the National Consultative Ethics Committee for Health and Life Sciences, National Council of Ethics for the Life Sciences, and the Helsinki Declaration of 1975 concerning the privacy and confidentiality of personal data, all personal patient information was anonymized. Only the age, sex, and date of examination were known for each subject. All data were permitted by AP-HM for use in this study.

Variables

We selected 14 anatomical regions: basicranium, cranial vault, face, mandible, clavicle, scapula, sternum, ribs, cervical vertebrae, thoracic vertebrae, lumbar vertebrae, sacrum, coxal bone, and femur. Fractures on the basicranium comprise those of the cribriform plate of the ethmoid bone, the orbital plate of the frontal bone, the temporal bone, the sphenoid, and the occipital bone [10]. Given the definition of Cooper and Golfinos [10], and for the purposes of descriptive statistics, we only considered as vault elements: the frontal and parietal bones. The face is composed of the maxilla, the palatine, the vomer, the lacrimal bones, the nasal bones, and the zygomatic and the ethmoid bones without the cribiform plate. We grouped together cervical vertebrae and hyoid bone [10, 11].

Skeletal trauma was described for each individual as follows: the skeletal element and anatomical location of the injury (to investigate the distribution of the fractures on the body).

To record the presence of fractures in each anatomical region, we used a binary scoring (0, absence/1, presence); however, to take into account the number of fractures, we used a three-staged scores: 0: absence of fractures, 1: single fracture, and 2: two fractures or more.

Each individual was reviewed in the three anatomical planes (axial, coronal, and sagittal) using the window viewing presets for bone and this was adjusted manually on AW Workstation (AW server 2.0; GE HealthCare, Milwaukee, WI, USA) and Horos (version 3.3.5®; https://horosproject.org). The 3D volume renderings were also used to identify the fractures.

Statistical analyses

Fisher's exact tests were used to identify the association between two qualitative variables and specially the correlation between the fracture and the sex or the age group. Then, we used the mean measure of divergence (MMD), which is the most common procedure for calculating distances (the mean variance) from a set of nonmetric traits recorded in binary scoring [12–14]. MMD values of more than twice their corresponding standard deviations (SDs) were considered to be statistically significant and allowed us to consider that compared samples diverge.

To compare the mean numbers of fractures of the two aetiologies for each anatomical region, the Mann–Whitney *U* test was used.

Using the number of fractures on the different anatomical regions recorded in three different stages (absence/presence of one fracture/presence of two fractures and more), a decision tree was built to predict the aetiology of these fractures (falls/blows).

All statistical analyses were performed using the R Software® version 3.3.2 (R Foundation for Statistical Computing, Vienna, Austria). For all statistical tests, the significant level used was 0.05. We used {AnthropMMD} R package to calculate the distance between the two aetiologies regarding the presence of fractures in 14 different anatomical regions. {rpart} R package was used to build the decision tree.

To assess the repeatability, we randomly selected 30 individuals of the sample. The presence and number of fractures were observed twice in 14 anatomical regions by the same observer, which was trained on Horos version 3.3.5®. Inter- and intra-observer variations were evaluated using Cohen's Kappa coefficient with {KappaGUI} R package.

Results

Inter- and intra-observer errors

The inter- and intra-observer errors were evaluated using Cohen's Kappa (Table 1) [15, 16]. A table taken from Landis and Koch [17] was used for agreeing to evaluation (Table 2).

The results show a perfect and substantial agreement for all variables. The lowest value of Cohen's Kappa for the presence/absence of the fracture is 0.65 and for the scoring in three stages is 0.65, too.

Characteristics of the sample

Our sample includes 235 falls and 165 blows from three hospitals, which were CT scanned from January 2008 to August 2019. We observed 190 males (80.85%) and 45 females (19.15%) in fall cases and 152 males (92.12%) and 13 females (7.88%) in blow cases (Supplementary Table S1). Fisher's

Table 1. Inter- and intra-observer errors of the assessment of the presence and the number of fractures on 14 anatomical regions using Cohen's Kappa.

Anatomical region	Absence/presence		Absence/simple/multiple	
	Inter-observer	Intra-observer	Inter-observer	Intra-observer
Basicranium	0.71	1.00	0.72	1.00
Cranial vault	0.84	1.00	0.84	1.00
Face	0.90	0.90	0.91	0.82
Mandible	0.87	1.00	0.75	1.00
Clavicle	1.00	0.65	1.00	0.65
Scapula	0.84	1.00	0.84	1.00
Sternum	–	–	–	–
Ribs	0.72	1.00	0.68	0.93
Cervical V.	1.00	1.00	1.00	1.00
Thoracic V.	0.76	0.84	0.77	0.68
Lumbar V.	0.92	1.00	0.92	0.93
Sacrum	1.00	1.00	0.86	1.00
Coxal	1.00	0.87	1.00	0.87
Femur	1.00	1.00	1.00	1.00

–: The Kappa was not provided because the calculation made no sense. V.: vertebrae.

Table 2. Cohen's Kappa agreement (data from Landis and Koch [17]).

Kappa (*K*)	Strength of agreement
<0	Disagreement
0.00–0.20	Insignificant
0.21–0.40	Low
0.41–0.60	Middle
0.61–0.80	Good
0.81–1.00	Very good

exact test shows that the proportion of males significantly differs between the two aetiologies (80.85% *vs.* 92.12%, $P = 0.001$).

Regarding the age distribution, we found that adults aged 40–49 years involved in falls are more frequent (43.83%) than the two other age groups (27.66% for individuals between 30 and 39 years; 28.51% for the group of 20–29 years). Among the blow cases, almost the half (46.67%) was 20–29 years old, 33.33% of individuals aged 30–39 years and 20.00% of individuals aged 40–49 years (Supplementary Table S2).

Fisher's exact test shows a significant difference in the distribution of the individuals by age group between the two aetiologies ($P < 0.001$).

Skeletal fractures: circumstances, incidence, topography

An examination of the distribution and frequency of skeletal fractures showed that almost all skeletal elements were susceptible to fracture in both aetiologies (Tables 3 and 4, Figure 1).

Among the 235 falls, 34.89% of cases exhibited trauma to a single region and 65.11% of cases exhibited polytrauma. Among the 165 blows, 67.27% of cases exhibited trauma to a single region, and 32.73% of cases exhibited polytrauma (Table 3).

We observed that fractures occurred more frequently on the cranial vault, the basicranium, the clavicle, the scapula, the sternum, the ribs, the cervical vertebrae, the thoracic vertebrae, the lumbar vertebrae, the sacrum, the coxal bone, and the femur in falls, while fractures of the face (64.24%) and of the mandible (38.79%) occurred more often in blows (Table 4, Figure 1).

Table 3. Anatomical regions fractured by aetiology (*N*=400).

Aetiology	One AR fractured *n* (%)	More than one AR fractured *n* (%)
Falls (*n* = 235)	82 (34.89)	153 (65.11)
Blows (*n* = 165)	111 (67.27)	54 (32.73)

AR: anatomical regions.

Table 4. Presence of fractures by anatomical region in both aetiologies (*N* = 400).

Region	Falls (*n* = 235) *n* (%)	Blows (*n* = 165) *n* (%)	*P*-value
Basicranium	63 (26.81)	36 (21.82)	0.290
Cranial vault	47 (20.00)	16 (9.70)	**0.005**
Face	79 (33.62)	106 (64.24)	**<0.001**
Mandible	14 (5.96)	64 (38.79)	**<0.001**
Clavicle	9 (3.83)	0 (0.00)	**0.012**
Scapula	27 (11.49)	1 (0.61)	**<0.001**
Sternum	15 (6.38)	0 (0.00)	**<0.001**
Ribs	63 (26.81)	5 (3.03)	**<0.001**
Cervical V.	14 (5.96)	0 (0.00)	**<0.001**
Thoracic V.	47 (20.00)	3 (1.82)	**<0.001**
Lumbar V.	82 (34.89)	8 (4.85)	**<0.001**
Sacrum	49 (20.85)	0 (0.00)	**<0.001**
Coxal	54 (22.98)	2 (1.21)	**<0.001**
Femur	20 (8.51)	0 (0.00)	**<0.001**

P-value is associated with the Fisher's exact test; significant values are given in bold. V.: vertebrae.

Fractures of the face, the thoracic and lumbar vertebrae, the sacrum, and the coxal bone were significantly associated with sex. Fractures on the mandible, the ribs, and lumbar vertebrae were significantly associated with age (Table 5).

The MMD was calculated from the presence/absence of fractures in the 14 anatomical regions. The MMD value (0.341) is greater than twice the SD (0.004), indicating a significant difference between falls and blows.

Number of skeletal fractures

Concerning the minimum number of fractures in the 14 anatomical skeletal regions, we worked in two steps. First, we compared the mean number of fractures occurring in falls and blows (Table 6). The results show a significant difference between falls and blows based on the number of fractures on

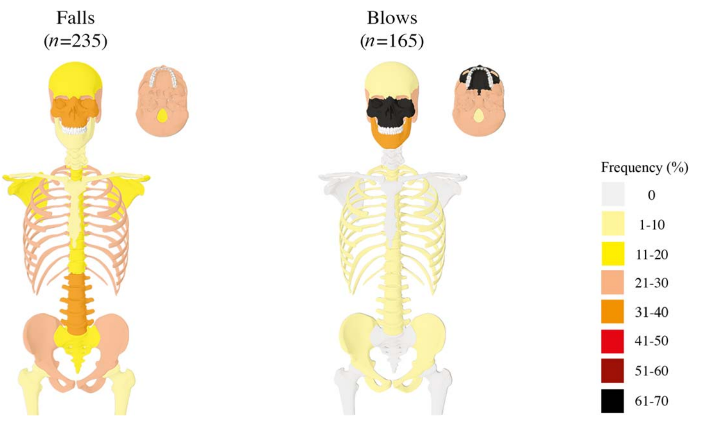

Figure 1. The frequency and distribution of fractures as related to the aetiology.

Table 5. Presence (%) of fractures by anatomical region, sex, and age ($N = 400$).

Region	Sex		*P*-value	Age (year)			*P*-value
	Female ($n = 58$)	Male ($n = 342$)		20–29 ($n = 144$)	30–39 ($n = 120$)	40–49 ($n = 136$)	
Basicranium	22.41	25.15	0.743	28.47	23.33	22.06	0.440
Cranial vault	15.52	15.79	1.000	19.44	15.00	12.50	0.279
Face	32.76	48.54	**0.032**	47.92	47.50	43.38	0.711
Mandible	12.07	20.76	0.152	27.08	21.67	9.56	**<0.001**
Clavicle	1.72	2.34	1.000	2.08	1.67	2.94	0.839
Scapula	5.17	7.31	0.782	4.17	6.67	10.29	0.135
Sternum	5.17	3.51	0.465	3.47	1.67	5.88	0.223
Ribs	18.97	16.67	0.705	9.03	18.33	24.26	**0.002**
Cervical V.	5.17	3.22	0.438	2.78	4.17	3.68	0.840
Thoracic V.	25.86	10.23	**0.002**	10.42	12.50	14.71	0.548
Lumbar V.	36.21	20.18	**0.010**	15.97	21.67	30.15	**0.018**
Sacrum	22.41	10.53	**0.016**	10.42	12.50	13.97	0.670
Coxal	24.14	12.28	**0.023**	10.42	20.00	12.50	0.075
Femur	8.62	4.39	0.188	4.86	5.83	4.41	0.882

P-value is associated with the Fisher's exact test; significant values are given in bold. V.: vertebrae.

Table 6. Comparison of the mean number of fractures by anatomical region according to the cause of the trauma.

Region	Falls		Blows		*P*-value (Mann–Whitney *U* test)
	[Min;max]	Mean (SD)	[Min;max]	Mean (SD)	
Basicranium	[0;7]	0.762 (1.629)	[0;8]	0.467 (1.182)	0.295
Cranial vault	[0;4]	0.366 (0.833)	[0;4]	0.212 (0.651)	**0.023**
Face	[0;8]	0.813 (1.614)	[0;6]	1.370 (1.639)	**<0.001**
Mandible	[0;2]	0.111 (0.439)	[0;2]	0.558 (0.768)	**<0.001**
Clavicle	[0;2]	0.060 (0.315)	–	–	–
Scapula	[0;2]	0.174 (0.514)	[0;1]	0.006 (0.078)	**<0.001**
Sternum	[0;2]	0.077 (0.311)	–	–	–
Ribs	[0;21]	1.362 (2.980)	[0;13]	0.230 (1.455)	**<0.001**
Cervical V.	[0;11]	0.157 (0.880)	–	–	–
Thoracic V.	[0;13]	0.545 (1.511)	[0;2]	0.030 (0.232)	**<0.001**
Lumbar V.	[0;12]	1.132 (2.007)	[0;7]	0.127 (0.709)	**<0.001**
Sacrum	[0;4]	0.391 (0.847)	–	–	–
Coxal	[0;2]	0.409 (0.776)	[0;2]	0.018 (0.174)	**<0.001**
Femur	[0;4]	0.149 (0.538)	–	–	–

In bold: significant values; –: no fracture was observed, so the comparison was not possible. V.: vertebrae; SD: standard deviation.

all anatomical regions except the basicranium. Fractures are more numerous in falls than in blows except for the face and the mandible.

Then, we synthesized the minimum number of fractures by a new scoring: 0: absence of fracture, 1: single fracture, and 2: more than two fractures.

Single fractures are more widespread in fall cases than in blow cases (Table 7, Figure 2A).

Fall cases exhibited widespread simple fractures with close frequencies (between 1.28% and 8.51%) even for the face, which presents 12.77% of fractures, and the basicranium, which presents 12.77% of fractures (Figure 2A, Table 7).

Table 7. Number (%) of fractures recorded in three stages present in the anatomical region, in both aetiologies ($N = 400$).

Region	Falls ($n = 235$)		Blows ($n = 165$)		*P*-value
	Simple (n, %)	Multiple (n, %)	Simple (n, %)	Multiple (n, %)	
Basicranium	30 (12.77)	33 (14.04)	17 (10.30)	19 (11.52)	0.529
Cranial vault	20 (8.51)	26 (11.06)	4 (2.42)	12 (7.27)	**0.012**
Face	30 (12.77)	42 (17.87)	28 (16.97)	66 (40.00)	**<0.001**
Mandible	4 (1.70)	10 (4.26)	32 (19.39)	32 (19.39)	**<0.001**
Clavicle	3 (1.28)	6 (2.55)	0 (0.00)	0 (0.00)	**0.018**
Scapula	13 (5.53)	14 (5.96)	1 (0.61)	0 (0.00)	**<0.001**
Sternum	12 (5.11)	3 (1.28)	0 (0.00)	0 (0.00)	**<0.001**
Ribs	7 (2.98)	56 (23.83)	0 (0.00)	5 (3.03)	**<0.001**
Cervical V.	5 (2.13)	9 (3.83)	0 (0.00)	0 (0.00)	**0.002**
Thoracic V.	16 (6.81)	31 (13.19)	1 (0.61)	2 (1.21)	**<0.001**
Lumbar V.	17 (7.23)	65 (27.66)	4 (2.42)	4 (2.42)	**<0.001**
Sacrum	16 (6.81)	33 (14.04)	0 (0.00)	0 (0.00)	**<0.001**
Coxal	12 (5.11)	42 (17.87)	1 (0.61)	1 (0.61)	**<0.001**
Femur	10 (4.26)	10 (4.26)	0 (0.00)	0 (0.00)	**<0.001**

P-value is associated with the Fisher's exact test; significant values are given in bold. V.: vertebrae.

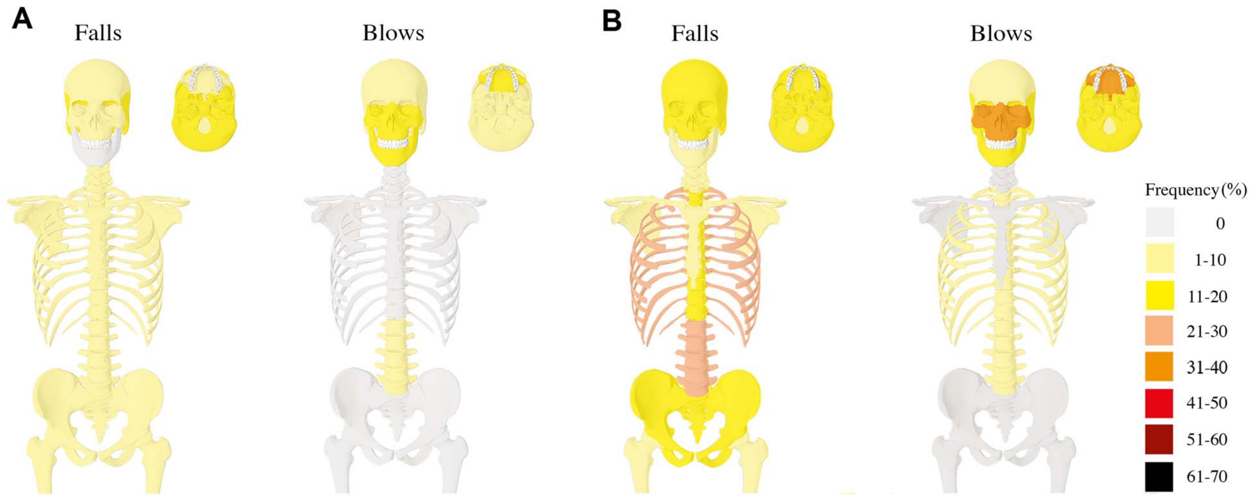

Figure 2. The frequency and distribution of simple (A) and multiple (B) fractures as related to the aetiology. Falls: $n = 235$; blows: $n = 165$.

In blow cases, only five anatomical skeletal regions are concerned by simple fractures, with a frequency > 1%: the basicranium (10.30%, $n = 17$), the cranial vault (2.42%, $n = 4$), the face (16.97%, $n = 28$), the mandible (19.39%, $n = 32$), and lumbar vertebrae (2.42%, $n = 4$) (Figure 2A, Table 7).

Fractures of the basicranium occurred more frequently in falls than in blows (12.77% *vs*. 10.30%) (Table 7, Figure 2A).

Fall cases exhibited again widespread multiple fractures (Table 7, Figure 2B). Multiple fractures are more frequent in lumbar vertebrae (27.66%, $n = 65$), then by decreasing frequency in ribs (23.83%, $n = 56$), face and coxal (17.87%, $n = 42$; for both), and sacrum and basicranium (14.04%, $n = 33$; for both), The mandible is more concerned by multiple fractures than simple ones (4.26% *vs*. 1.70%) (Table 7, Figure 2B).

Multiple fractures in blows are more localized and involved seven anatomical regions with a frequency > 1%: the face (40%, $n = 66$), the mandible (19.39%, $n = 32$), the basicranium (11.52%, $n = 19$), the cranial vault (7.27%, $n = 12$), the ribs (3.03%, $n = 5$), the lumbar vertebrae (2.42%, $n = 4$), and the thoracic vertebrae (1.21%, $n = 2$). No multiple fractures were observed on the clavicle, scapula, sternum, cervical vertebrae, sacrum, and femur (Table 7, Figure 2B).

A decision tree was built to identify the criteria playing a key role in the distinction between blows and falls (Figure 3). For this purpose, the number of fractures according to the three stages in 14 anatomical regions were used as independent variables of the model. The decision tree of our study integrated all 400 cases.

The three variables identified by the decision tree were the number of fractures on the mandible, on the face, and on the cranial vault. For each branch, the numbers of falls and blows are indicated (Figure 3). Given that 28 cases of blows and 54 cases of falls were misclassified, the misclassification rate with the leave-one-out method was equal to 20.5%.

Therefore, the decision tree correctly classified 79.5% of the total cases (77.02% (181/235) of falls and 83.03% (137/165) of blows). Perfect discrimination remains unrealistic, but the decision tree shows a strong discrimination potential between fall and blow cases using the number of fractures on the mandible, face, and cranial vault.

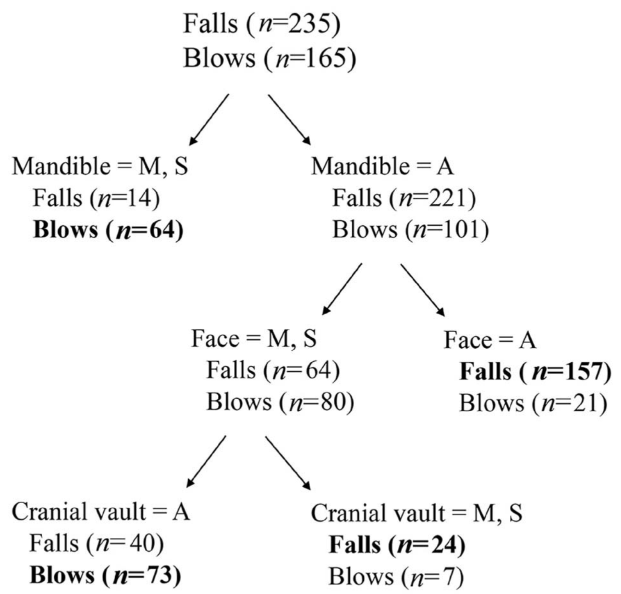

Figure 3. Decision tree (A: no fracture, S: simple fracture, M: multiple fractures).

Discussion

Repeatability

The results showed a perfect and substantial agreement for all the variables.

Fracture location, sex, and age

The presence of fractures by anatomical region, sex, and age (Table 5) showed that face fractures are found significantly more often for males. This is consistent with literature and with our sample distribution by sex and aetiology where males represent >90% of blow cases and with the fact that there is a significant tendency for face fractures to be caused by blows (Table 4) [18–20]. Concerning the thoracic and lumbar vertebrae, as well as the coxal and sacrum, there is a statistically significant difference showing that these bones are more often fractured in women (Table 5). Once again, this appears to be consistent with the fact that these bones are more often fractured in case of falls (Table 4) and that there is almost three times more women in our sample affected by falls. This prevalence of fracture can be explained by differences in bone structure between the sexes (influenced, among other things, by osteoporosis, pregnancy, or lactation) [21–25]. Finally, concerning age, Table 5 shows that the mandible is significantly less fractured when age increases, and this makes sense with the fact that mandible fracture is associated with blows (Table 4) and blows decreases with age [26–34]. On the contrary, Table 5 shows that ribs and lumbar vertebrae are significantly more often fractured with increasing age, and these bone fractures are associated with falls (Table 4) that increase with age (Figure 2A) [35, 36].

Skeletal fractures: circumstances, incidence, and topography

In this study, fractures occurred more frequently in falls for the postcranial skeleton, the basicranium, and the cranial vault. Conversely, the fractures of the face and the mandible were more frequently found in blows.

Falls

In fall cases, males are more frequent (80.85%) than females (19.15%) and the number of falls increases with age. Indeed, 43.83% of the population aged between 40 and 49 years (n = 103) compared to 28.51% of individuals aged 20–29.

These observations enabled us to highlight those fractures are more frequent and better distributed over the skeleton in fall cases. According to Kratter [37], falls cannot cause injuries of the vertex area nor the cranial vault (above the line binding the frontal eminence, the parietal eminence, and the external occipital protuberance) except in the case of a fall from a height or an impact against an edge or a corner [38, 39].

Simple fractures (i.e. single fractures) are more common in the face (12.77%) and the base of the skull (12.77%).

Multiple fractures are rather well distributed on the skeleton even if they present a lower frequent localization compared to the ribs (23.83%) and the lumbar vertebrae (27.66%).

The minimum number of fractures on the scapula, ribs, coxal bone, thoracic, and lumbar vertebrae is significantly more critical in falls. These results are perfectly consistent with the literature [3, 21, 39–46].

Blows

In blow cases, males are more frequent (92.12%) than females (7.88%) and the number of blows decreases with age. Indeed, 46.67% of individuals aged 20–29 years have at least one fracture compared to 20.00% of individuals aged 40 to 49. In 2001, Walker [26] noted that people involved in assaults tend to be young males.

Fractures on the skeleton are located on the face (64.24%) and the mandible (38.79%).

Simple fractures show prevalence for the same anatomical regions, presenting, respectively, 16.97% and 19.39%. Multiple fractures are more frequent in the face (40.00%), mandible (19.39%), and basicranium (11.52%).

The minimum number of fractures on the face and the mandible is significantly higher in blows.

These results are concordant with the literature since the head and face are the main rage focus of the perpetrator because these areas are psychologically linked to the victim's identity [47–50].

However, our results are divergent from Kratter [37] who showed that blows can cause injury in every region of the head with the exception of the base of the skull [38, 39].

Cranial vault

Our results showed that fractures in the cranial vault occurred more frequently in fall cases (19.57%, n = 46) than in blows (9.70%, n = 16).

Many studies showed that fractures and injuries on the cranial vault and above the HBL could not result from falls except in cases of repeated falls, falls from a height, or an impact against an edge or a corner; so they would be less frequent than in blow cases [6–9, 38, 39, 51, 52]. However, our results showed the opposite.

Basicranium

Our results showed that fracture on the basicranium occurred more frequently in fall cases (26.81%, n = 63) than in blow cases (21.82%, n = 36).

According to Kratter [37], blows can cause injury in every region with the exception of the base of the skull [39]. However, Rogers [53] wrote that basilar skull fractures could result indirectly from blows to the front of the head or through compression of the spine against the base of the skull. Our results confirmed these latest findings.

Face

Our results showed that fractures in the face occurred more frequently in blow cases (64.24%, n = 106) than in falls (33.62%, n = 79). Concerning blow cases, this result is concordant with those of many authors who said that one of the most commonly sustained injuries is to the face [18, 26].

According to Arabion et al. [54], the most frequent aetiology of facial fractures is falling, while for other studies, it is traffic-related [19, 54–57]. However, based on the study of Guyomarc'h et al. [7], one of the criteria pointing towards blows is the presence of facial fractures. Several authors agree that showing that violence is the most frequent cause of craniofacial fractures, and our results are consistent with this [20, 27, 58–63]. Our results showed that adult males are more frequently implied, whatever the aetiology is [18–20].

Mandible

Fractures on the mandible occur in 38.79% (n = 64) of blow cases and 5.96% (n = 14) of fall cases. Our results are similar to those of many studies showing that most fractures were caused by assault followed by falls [27–30] and are more frequent in young males (20–30 years old) [31–34].

Clavicle

Clavicle fractures were only observed in fall cases (3.83%, n = 9) with a predominance in males. These results are concordant with the literature. Clavicle fractures occur from sports, falls, and motor vehicle accidents [21, 40, 64–66]. According to Sirin et al. [67], this injury occurs more frequently in males than in females, with the highest incidence in the 20- to 30-year-old age group, which is similar to our study.

Scapula

Scapula fractures occur in 11.49% (n = 27) in fall cases and 0.61% (n = 1) in blows with a predominance in people aged 40 and 49 years (10.29%, n = 14). According to the literature, scapula fractures are uncommon and result from falls or motor vehicle incidents [3, 21, 40]. People aged 40–60 years are more implied, which is concordant with our results [3, 21, 68].

Rib

In our study, rib fractures are more frequent in fall cases (26.81%, n = 63) than in blow cases (3.03%, n = 5). People aged 40 and 49 years are more implied by this type of fracture.

According to the literature, rib fractures are common injuries and result from sports (stress fractures) and minor injuries (especially in elderly individuals) [69, 70] or from homicidal actions, particularly stomping on the chest of a prone victim or a direct blow or kicking and from cardiopulmonary resuscitation [64, 71]. Fractures in the upper zone of the thoracic cage (one to fourth ribs) require high-velocity trauma [69]. Rib fractures are complex and are an essential indicator of trauma severity (morbidity and mortality increase with increasing numbers of ribs fractured) [69, 72–74].

Sternum

In our sample, sternum fractures only occur in fall cases (6.38%, n = 15). According to the literature, sternal fractures can result from motor vehicle accidents, contact sports, falls, and assaults [72, 74, 75].

Vertebrae

In our sample, there are no cervical fractures in blows, but in falls they have a frequency of 5.96% (n = 14). Overall, spinal fractures frequently occur in falls [40]. Cervical fractures are frequent in motor vehicle accidents, sporting accidents, and assaults with weapons [21]. During an attack, these kinds of fractures are more due to the fall [76–78].

In our sample, fractures on thoracic and lumbar vertebrae are more frequent in fall cases than in blows. According to the literature, thoracolumbar injuries are due to motor vehicle accidents and fall from a significant height [21, 41–46].

The thoracolumbar fractures are more frequent in females. These significant differences between males and females can be explained by structural and kinetic differences, "probably an evolutional allowing female to carry their fetus while standing in an upright position" [22]. Indeed, females display a lumbar hyperlordosis, a thoracic hypokyphosis and a lesser lumbar range of motion in flexion–extension [22]. These elements limit the prevalence of cervical spine fracture and can be the cause of lumbar spine fractures in females. Moreover, according to many authors, during pregnancy and lactation, females lose 3%–10% of trabecular bone [79].

Sacrum

Our results show that sacral fractures only occur in fall cases (20.85%, n = 49) and are more frequent in females (22.41%, n = 13).

According to the literature, fractures of the sacrum can be caused by a stress fracture or insufficiency fracture [53, 80]. This last fracture occurs within normal stress on the bone. The bone can be weakened by pregnancy and lactation, radiation therapy, rheumatoid arthritis, osteoporosis (which can also be caused by some medications or diseases), demineralization in elderly patients, and postmenopausal females [21, 23–25]. Sacral fracture frequently occurs in motor vehicle accidents and falls and are more frequent in females [81–85].

Coxal bone

In our study, fractures of the coxal bone are more frequent in falls (22.98%, n = 54) and in females (24.14%, n = 14).

Pelvic fractures in adults are associated with significant morbidity and mortality [3, 86]. Pelvic fractures are most common in young adult males and older males and females [87, 88]. The prevalence of pelvic fractures is male for Pereira et al. [89] and female for Buller et al. [90], Sanders et al. [91], and Melton et al. [92]. According to Balogh et al. [93], pelvic fractures in males occur more frequently in high-energy accidents (motor vehicle accidents), and for females, these occur in low-energy injuries. Pelvic fractures are common in motor vehicle accidents, falls, and sport-related accidents [3, 21, 40].

Femur

This study shows that fractures of the proximal femur only occur from falls (8.51%, n = 20).

As for the coxal bone and sacrum, insufficiency fractures can occur on the proximal extremity of the femur [94]. In young adults, femur fractures result from motor vehicle accidents, falls from heights, or sports [3, 21, 40, 95].

The skull: an important anatomical region in the distinction between falls and blows?

A significant amount of research has been devoted to understanding the biomechanics of fractures by powerful forces [96–98], but few studies have focused on the evaluation of the origin of the trauma by analysing the fracture location and morphology [6–9, 51, 99–102]. This is why it is necessary to deepen our knowledge in this field. Blunt force injuries located in the cranium and in the trunk are preferentially associated with interpersonal violence. They are often linked with the manner and cause of death, which makes their examination crucially important in the medicolegal investigation of death circumstances [4, 5, 48–50, 99, 103–105].

One of the first authors who tried to distinguish between falls and blows based on the skull lesions, in 1905, was Richter [106]. He highlighted the attention that must be paid to the amount of skin bruises and their location. If there are particular reasons for repeated falls, if the bruises are numerous and are located in regions that cannot be involved in cases of a fall (the cranial vertex), we can hypothesize that the child is beaten.

In 1921, Kratter's researches (as cited by Fracasso in 2011) showed falls can cause injuries to the vertex area and cranial vault when the fall was from a great height or if there was an impact with an obstacle during the fall [38, 39].

Regarding a similar line, Walcher, in 1931, created the HBL rule which says that fall-related injuries do not lie above the HBL when some conditions are fulfilled (standing position of the individual before falling, flat floor without incline or stairs, falling from one's height, and absence of intermediate obstacles), but the rule is not applicable for small children [38, 52].

Nowadays, the HBL is defined as the area above the Frankfort horizontal plane, which is located between the line passing through the glabella (G-line) and the line passing through the centre of the external auditory meatus (EAM-line) [51] (Figure 4).

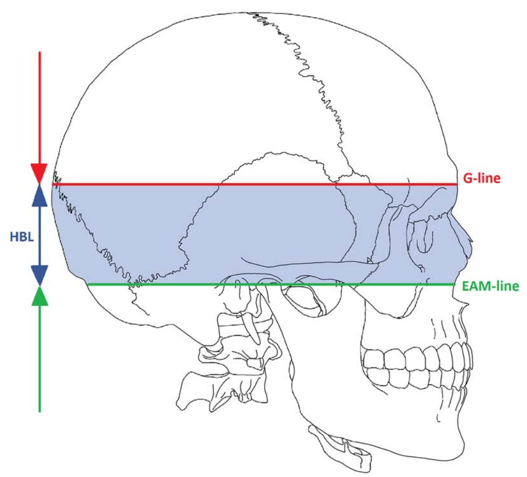

Figure 4. The hat brim line (HBL), area located between the G-line (the superior margin) and EAM-line (the inferior margin).

The use of the HBL rule in the distinction between falls and blows is controversial. Despite this, some studies have used this rule when observing skull fractures and skin lesions.

The few studies that have compared falls and blows cases in relation to the HBL to determine the validity of this rule are those cited below.

Ehrlich and Maxeiner [8, 9], Kremer et al. [6, 51], and Guyomarc'h et al. [7] undertook studies to distinguish between falls and blows in blunt head traumas. Ehrlich and Maxeiner [8, 9] studied 254 falls (203 on a flat surface, 51 downstairs) and 51 blows. They observed that lacerations from blows occur more often above the HBL (55%) than lacerations from falls (33%).

Kremer et al. [6, 51] focused on the location of cranial fractures and number of lacerations. In Kremer et al. [51], 36 falls (23 from one's own height, 13 downstairs) and 44 blows were observed. The results showed that injuries from blows are more often found above HBL, although this rule should be used with caution. In Kremer et al. [6], 50 falls were observed (29 from one's height, 21 downstairs) and 64 interpersonal violence with a blunt weapon. The study confirmed that injuries inflicted by blows are often situated above HBL, a laceration inside HBL is more in favour of a fall (66.7%), and a skull fracture inside HBL is found equitably in both aetiologies.

Guyomarc'h et al. [7] described the number and length of lacerations on the entire skull, type of skull fractures, location of injuries, and the presence or the absence of postcranial injury in 50 cases of falls (29 from own height, 21 downstairs) and 63 cases of homicidal blows. The results showed a strong discrimination potential between fall and blow cases with four criteria, including the presence of fractures above the HBL (in favour of blows).

The authors confirmed that HBL has to be used carefully and not as a single criterion in the distinction between falls and blows. Perfect discrimination remains unrealistic, and before we can quickly and accurately distinguish falls from blows, there is a lot more work to be performed. Moreover, we have to be careful as some studies have a weak sample.

Besides, we find more fractures related to falls than to blows above this HBL, so the use of the HBL rule is limited. In both cases, the face is the anatomical region of the skull which is more frequently touched by fractures. Concerning the basicranium, the frequency of occurrence of fractures is similar in both aetiologies. Finally, the presence of fractures on the mandible is an important element to strengthen the hypothesis of blows struck at the individual.

The decision tree proposed in our study showed the importance of fractures located on the mandible, on the face, and on the cranial vault because it allows a distinction between blows and falls. By using this tree on our study sample to predict the aetiology of fractures, and taking care to use a "Leave One Out" procedure, the decision tree correctly classified 79.5% of the cases.

Some of these anatomical regions were already used in the "combined criteria tools" of Guyomarc'h et al. [7], which considered the number of scalp lacerations, the scalp laceration length, the vault fracture type, and the presence or absence of facial fractures. Their decision tree classified 82% of falls and 93.7% of blows correctly.

However, it should be noted that these two studies did not take into account certain parameters that can affect bone fractures (such as one's character or region). Indeed, some authors have shown that the risk of fracture and their location are related to ethnicity [107–109].

Conclusion

It seems that the HBL rule should be used with caution, but this preliminary stage of our work has shown that there is nevertheless a possibility of discussing the aetiology of blunt fractures, with the presence of fractures either on the cranium alone, or on the cranium and the postcranium.

We can use parameters like the anatomical location and the minimum number of fractures by anatomical regions to distinguish falls and blows even if several other parameters remain to be integrated (as the typology of fractures).

Ultimately, the goal is to develop a rating system that allows us to further refine the prediction of the aetiology of blunt fractures found during the postmortem study of skeletons.

However, our study showed that the skull is not the only anatomical region showing a significant difference between falls and blows.

Indeed, the postcranial regions play a role in the distinction of the two aetiologies, and more particularly, scapula, ribs, coxal bone, and thoracic and lumbar vertebrae.

Finally, we are perfectly aware that this is a preliminary study and that, for instance, there might be a relationship between the location of fractures caused by blows and with one's ethnicity, character, and region. These results should be qualified and we look forward to extend our sample to other populations.

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Authors' contributions

Mélanie Henriques carried out the study, performed the statistical analysis, and drafted the manuscript; Bérengère Saliba-Serre participated in the statistical analysis and revised the manuscript; Laurent Martrille contributed materials from Nancy and revised the manuscript; Alain Blum contributed materials from Nancy; Kathia Chaumoître contributed materials from Marseille; Paulo Donato and Nuno Campos contributed materials from Coimbra; Eugénia Cunha and Pascal Adalian both participated in the study's design and coordination and revised the manuscript. All authors contributed to the final text and approved it.

Compliance with ethical standards

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Ethics Committee of Faculdade de Medicina da Universidade de Coimbra, Portugal (protocol code: 026-CE-2019 and date of approval: 25/03/2019).

Data availability

The data for this study are kept by the first author.

Disclosure statement

Eugénia Cunha initial holds the position of Editorial Board Member for *Forensic Sciences Research* and is blinded from reviewing or making decisions for the manuscript.

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